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HEAVE AND LATERAL MOVEMENTS DUE TO PILE DRIVING

By D. Joseph Hagerty, A. M. ASCE and Ralph B. Peck, F. ASCE

INTRODUCTION

Whenever piles are driven, soil is displaced. The movements induced in the soil itself may have several undesirable consequences, including the lift or lateral displacement of those piles that have already been driven. The effects of pile and soil displacement on foundation performance depend in great extent upon the type of the piles and the way in which they transfer the load to the surrounding ground.

If the piles are designed to be end-bearing, their rise during the driving of subsequently installed piles may seriously impair their load carrying capacity. The ensuing pile settlement may be at least as great as the pile heave. If piles are grouped in clusters beneath a structure, differential settlement among the heaved piles may be large and detrimental to the support of the structure.

When piles are to support loads by skin friction, the detrimental effect of pile heave may be less pronounced because there is no bearing stratum which the tip of the pile loses contact. Nevertheless, the strength and compressibility of the soil are altered by the displacements, with effects not fully understood (3,20,23).

Pile driving displaces soil and previously driven piles laterally as well vertically. Existing structures also may be displaced by the pile drive (6,9,10,26). The tops of driven piles may be displaced from their design locations by distances which greatly exceed the location tolerances in the foundation construction specifications. Moreover, where a pile contains an element, such as a slip joint in a composite pile or a splice in a timber pile, lateral soil displacement may produce a sharp kink and may decrease capacity of the pile (16).

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This paper presents the results of a study of heave involving case histories from private files and the engineering literature. Thirteen suitable cases were found. They are:

Cases from Private Files.
Case A1—Chicago; Steel-frame structure; insensitive soft clays over hard clays and compact silts.
Case A2—Cleveland; Bridge pier; insensitive medium to hard saturated clays.
Case A3—St. Louis; Office buildings; insensitive soft silty clays and clayey silts over weathered limestone.
Case A4—Chicago; Warehouse extension; insensitive saturated soft to medium clays.
Case A5—Great Britain; Power station; insensitive soft to medium clays.

Cases from Engineering Literature.
Case B1—Western Canada; Pulp mill extension (8); variable glacial deposits over sand-gravel outwash.
Case B2—Cleveland; Blast furnace foundation (13); fill over sand and gravel, overlying medium to stiff blue clay.
Case B3—Backa, Sweden; Foundations at three sites (14,27); deep deposits of soft normally-loaded sensitive clay.
Case B4—Detroit; Expressway pier (3); deep deposit of soft blue clay, sensitive along upper 20 ft of 80-ft long piles.
Case B5—Mexico City; Building foundation (30,31); deep deposit of soft insensitive clay.
Case B6—Utah; Willard Pumping Plant (5,28,29); lean insensitive soft to medium clays with sand and silt layers.
Case B7—Boston; Insurance building (1,2); deep deposit of saturated insensitive soft clay.
Case B8—Tokyo; Telephone building (4); loose sand layers over a deposit of soft silty clay and medium clay.
Case B9—Detroit; Pumping station (24); deep deposit of soft insensitive clay.

The first part of the paper deals with movements of soil during pile driving, and the second with movements of piles already driven. The intention herein is to present specific aspects of heave and lateral movements due to pile driving. Recognition of the nature of such movements should suggest appropriate preventive and remedial measures; therefore, specific remedial measures are not recommended herein.

DISPLACEMENT OF SOILS

Previous studies suggest that net soil displacement is likely to be small when piles are driven into clean granular soils (7,12,19). On the other hand, significant soil displacement occurs during pile driving in fine-grained soil deposits.

Analysis of the collected data leads to the conclusion that saturated, insensitive clay soils behave incompressibly during pile driving; i.e., the volume of displaced soil is equal to the volume of the inserted piles. On may be described in some detail to support this conclusion.

Figs. 1 and 2 show, respectively, a plan view and a soil profile for a pile foundation consisting of step-taper piles driven behind a bulkhead into a soft clay deposit. The piles nearest the bulkhead were driven first and subsequent driving was successively farther from the water. The riverward piles were

![FIG. 1.—PLAN, WAREHOUSE ADDITION, CASE A4](image1)

![FIG. 2.—SECTION THROUGH FOUNDATION, CASE A4](image2)
been approximately 23 in. The average displacement along the entire bulkhead between column lines 16 and 26 was about 21-1/2 in. However, some movement had occurred at the west end of the bulkhead before the location surveys were initiated. Considering only that portion of the bulkhead between column lines 22 and 26, where the location surveys were begun before any piles were driven behind the bulkhead, the average measured displacement was about 24 in.

The movements of the various rows of foundation piles were estimated in a similar manner. Table 1 shows a comparison between computed and measured movements.

Lateral movements of the soil toward the river completely account for the volume of the piles. Thus it appears that the insensitive clay soil into which the piles were driven behaved incompressibly during pile driving.

TABLE 1.—PILE MOVEMENTS, CASE A4

<table>
<thead>
<tr>
<th>Pile row</th>
<th>Computed movement, in inches</th>
<th>Measured movement, in inches</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>15</td>
<td>14</td>
</tr>
<tr>
<td>AB</td>
<td>12</td>
<td>11-1/2</td>
</tr>
<tr>
<td>B</td>
<td>7-1/2</td>
<td>8</td>
</tr>
<tr>
<td>BC</td>
<td>1-1/2</td>
<td>2-1/2</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

FIG. 3.—DISPLACEMENT OF BULKHEAD, CASE A4

The values of heave of the ground surface observed at four other sites where piles were driven into insensitive, saturated clays indicate that approximately half the volume of displaced soil appeared as surface heave within the area of the pile foundation, while the remaining half appeared as surface heave outside the foundation area. The data are shown in Fig. 4. The soil heave in each case was divided by the length of the piles to obtain the normalized soil heave. To facilitate comparison of case history data, a volumetric displacement ratio was calculated for each case by dividing the total volume of the inserted piles by the volume of soil enclosed or surrounded by those piles. In Fig. 4 a significant correlation is apparent between the normalized soil heave and the volumetric displacement ratio. In the four cases designated A2, B4, B7, and B5, the piles were driven in a fairly regular sequence from one end of the foundation to the other, and the ground surface from which the piles were driven was practically level.

Given the conditions of a saturated insensitive clay soil, a regular pile driving sequence, and a level foundation ground surface, it is concluded that the soil surface heave within the foundation area may be estimated by the following procedure:

1. The volumetric displacement ratio is calculated by dividing the total volume of the inserted piles by the volume of soil enclosed by the pile foundation.
2. The normalized soil heave, equal to the soil heave divided by the pile length, is estimated empirically. For the conventional types and dimensions of piles and foundation arrangements studied in this investigation, the normalized soil heave was found to be approximately one-half the volumetric displacement ratio obtained in step 1.
3. The heave of the soil surface is estimated to be the product of the normalized soil heave and the average length of the piles.

This procedure is applicable only to those situations in which all the conditions mentioned are satisfied. The significance of changes in these conditions is indicated in the individual case histories.

Effect of Soil Characteristics.—Information from two cases, B3 and B5, indicates that when piles are driven into sensitive clays the pattern of soil displacement may differ from that produced in insensitive clays.

First, the disturbance of the soil may liquefy a sensitive clay soil around the pile as it is being driven. The liquefied soil may be extruded onto the ground surface around the pile. Such extrusion was noted in case B5 and has been reported elsewhere (11). The effect of such extrusion appears to be to reduce the heave of the soil surface beyond the limits of the area enclosed by the piles themselves and to confine the surface heave roughly within the area of the pile foundation. In both cases B3 and B5 the observed heaves of the soil
The centers of the foundations were approximately equal to those that would have been predicted for insensitive clay subsoils, as shown in Fig. 4. However, in case B3, the total volume of heaved soil amounted to less than 40% of the volume of the inserted piles, and surface heave outside the foundation area was negligible.

Second, some evidence was found in cases B3 and B5 that a significant amount of consolidation occurred in the disturbed sensitive clay soil during pile driving. The effect of such consolidation is to reduce the total volume of heaved soil. Thus, the low volume of displaced soil noted in case B3 may have been a result, at least in part, of consolidation of the sensitive clay during pile driving.

The data from cases B6 and B8 show that, when piles penetrated alternating strata of fine-grained soils and granular materials, the observed surface heave was much less than the heave that would have occurred in insensitive clay soils. In these cases there occurred only about one-fifth the amount of heave that would have been predicted on the basis of the procedure outlined above for insensitive clay soils.

Effect of Driving Sequence and Foundation Geometry.—The correlation between normalized soil heave and volumetric displacement ratio shown in Fig. 4 was obtained for foundations in which the soil surface was level everywhere and the piles were driven in fairly regular sequence from one end of the foundation to the other. Data from cases A1, A4, and B9 suggest that when large differences in elevation exist within the foundation area, the soil is laterally displaced preferentially toward the lower elevations and the soil heave at the upper elevations is correspondingly reduced.

Case B2 illustrates that if the sequence of pile driving involves first driving piles along the perimeter of the foundation, thereby tending to enclose the soil in the foundation, the heave of the soil surface in the central area of the foundation is increased to a value greater than that obtained in the procedure outlined above. Space limitations in connection with case B2 made it necessary to drive H-piles for a blast furnace foundation in a horseshoe pattern from the outside of the area toward the center. Pile heaves of as much as 11 in. were observed. Hence, the soil surface heave must have been equal to or greater than 11 in.

The piles penetrated fill, silt, and sand in addition to clay. If only the clay soils are considered, the total soil displacement, distributed uniformly over the area of the foundation itself, would have produced a surface heave of about 13 in. Thus, in terms of the parameters in Fig. 4, the ratio of normalized soil surface heave to volumetric displacement ratio was approximately unity. This ratio contrasts with the data in Fig. 4, wherein the value of the ratio is on the order of 0.5.

In summary, it may be concluded that soil displacements of significant magnitude occur when piles are driven into fine grained, impermeable soils. The principle factors affecting the magnitude of soil displacement in addition to the characteristics of the subsoil, appear to be the driving sequence of the piles and the geometry of the foundation.

DISPLACEMENT OF DRIVEN PILES

The following analysis of movements of piles already driven caused by subsequent driving is introduced with a presentation of a particular case wherein pile movements directly influenced the overall success of the foundation construction.

FIG. 5.—PLAN VIEW OF HOSPITAL FOUNDATION, CASE A1

FIG. 6.—SECTION THROUGH FOUNDATION, CASE A1

Case A1.—A large steel-frame structure was constructed on the west side of Chicago. The substructure consisted of pile-supported frames beneath reinforced concrete walls and columns. As the site was underlain by a thick...
deposit clay, the structure was designed to be supported on cast-in-place pile, which would penetrate through the soft clay and transmit the weight of the building to firm strata at depth. A plan of the structure is shown in Fig. 5.

The subsoils of the Chicago area have been described in general elsewhere (17).

The ground surface at the site was located at about El. 13 with respect to Chicago City Datum. The subsoils, as revealed by the exploratory borings, are shown in Fig. 6.

The piles were of a composite type consisting of a lower portion of 10-3/4-in. diam steel pipe at least 15 ft long, and an upper portion of 12-in. diam, 18-gage corrugated metal shell. They were driven in clusters of 3 to 16, beneath walls and individual columns, and were spaced at 3 ft center-to-center, both ways, within the individual clusters. The design load was 40 tons per pile.

The first phase of construction was excavation of the foundations to the levels shown in Fig. 5. The driving of the composite piles was then begun by four pile-driving rigs.

Driving proceeded without apparent difficulties for about 80 days, when it was discovered that some piles had been displaced vertically and laterally from their initial locations. At this time, approximately 80 % of the piles called for in the original foundation design had been driven. Systematic location and elevation surveys were begun on Day 85 and were conducted several times after the conclusion of pile driving on Day 122. These surveys showed that, in general, the piles stopped moving vertically after all driving on the job was completed. Some piles continued to move laterally, however, for as long as two months. With the exception of the piles in the northern wing of the struc-
reinforced concrete beams; (2) individual piles were subjected to static loads of 40 or 50 tons in an effort to test their capacity and to reseat them at their original elevations; and (3) some clusters which had been capped before the movement of driven piles was noticed were subjected to reseating loads as great as 900 tons.

In only two clusters, B-7 and D-5 (see Figs. 7 and 8), were the elevations of any piles established before all the piles in those clusters were driven. In cluster B-7, piles 1, 2, 3, and 5 were driven on Day 111 and piles 4, 6, 7, and 8 were driven on Day 112. The elevation of the top of pile 3 was first established on Day 111, after pile 5 was in place, and almost certainly caused pile 3 to be heaved. The heave of pile 3 caused by driving pile 5 was probably on the order of 1 in. or less; driving the last 4 piles in cluster B-7 and all the piles in cluster B-6 caused only 4-3/4 in. of heave of pile 3. The total heave of pile 3 may, therefore, be estimated as approximately 5-1/2 in.

The heave of pile 1 in cluster D-5 reflects principally the influence of pile driving within cluster B-7 and in cluster B-6 and cluster B-5. The measured heave for pile 3, 4-3/4 in., did not represent the total heave of pile 3, however, since pile 5 had been driven 3 ft away on Day 111, after pile 3 was in place, and almost certainly caused pile 3 to be heaved. The heave of pile 3 caused by driving pile 5 was probably on the order of 1 in. or less; driving the last 4 piles in cluster B-7 and all the piles in cluster B-6 caused only 4-3/4 in. of heave of pile 3. The total heave of pile 3 may, therefore, be estimated as approximately 5-1/2 in.

A second cluster in which total pile heave may be estimated is D-5. The driving sequence along line D was from west to east. Piles 1 and 2 in cluster D-5 were driven on Day 119 and their elevations were determined immediately after they were driven. The elevation of pile 1 was checked on Day 121, after driving all the piles in cluster D-5 and all the piles in cluster D-4. The elevation of pile 1 in cluster D-5 was checked on Day 121 and the pile was found to have heaved 4-1/8 in., the result of driving piles 3 through 9 in cluster D-4. Since pile 2 in cluster D-5 had been driven after pile 1, pile 1 would have been displaced by that driving also. The heave of pile 1 caused by the driving of pile 2 may be estimated as less than 1 in. because driving the other 7 piles in the cluster produced only about 4 in. of heave of pile 1. The total heave of pile 1 may, therefore, be estimated as about 5 in.

Thus, the heaves of pile 1 in cluster D-5 and pile 3 in cluster B-7 may be considered typical for the southeastern wing of the foundation and may be reliably estimated at 5 in. and 5-1/2 in., respectively.

The overall cluster-to-cluster effects of the pile driving are evident in the
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reco heaves of the piles in clusters C-6, C-5, and D-6. Fig. 9 shows the pile heaves which were produced in clusters C-6 and C-5 by driving the piles in cluster C-4 and in the clusters along lines B and D. Moreover, in cluster C-6 elevation surveys showed a definite settlement over a 17-day period after the initial heave observations. Such settlement probably occurred in other clusters between the times when the piles were driven and when they were subjected to reseating loads but was not noticed because of the lack of continued extensive elevation surveys.

Cluster D-6, Fig. 8, driven on Day 118 and Day 119, was heaved by adjacent driving. The elevations of the piles on cluster D-6 were established first on Day 118 or Day 119, immediately after they were driven, and were checked on day 120, Day 121, and Day 136. The check survey on Day 120 indicated that the piles had heaved by the amounts shown in Table 2.

Measurements were also made of the lateral movement of various piles on this project. The locations of the piles were not established, however, until all the piles within a cluster had been driven. Fig. 10 shows movements in cluster A-7 which was the last cluster in its vicinity to be driven. The piles within cluster A-7 continued to move laterally as much as 1 in. for as long as three days after they were driven. The piles were also probably displaced during within-cluster driving, most likely away from subsequent driving within the cluster, but no data are available concerning the magnitudes of such movements.

Fig. 11 shows the movements of the centers of gravity of the clusters in the southeastern wing of the structure between the day on which their locations were first determined and Day 133. It is apparent that: (1) The magnitude of movement shown for any cluster is directly related to the number and proximity of piles driven after the first location survey for that cluster; (2) clusters continued to move for some time after driving had ceased in the immediate vicinity; and (3) the directions of pile movement seem to have been governed primarily by the location of subsequent driving.

Many of the clusters in the central area of the foundations also moved laterally after all nearby driving had ceased. These include the clusters adjacent to the construction slope which descended from El. 8 to El. 0 (Fig. 5); cluster H-15, cluster I-15, and cluster J-15. Cluster H-15 was driven on Day 20, cluster I-15 on Day 27, and cluster J-15 on Day 30. The first location surveys were conducted on Days 25, 59, and 38 for clusters J-15, I-15, and H-15, respectively. These first surveys showed that no cluster of the three was displaced more than 1 in. from its design location. Then, between the days when the first surveys were conducted and Day 83, all three clusters moved toward the east even though no construction activity took place nearby during that time. Cluster H-15 moved 17 in.; cluster I-15 moved 24 in.; and cluster J-15 moved 15 in. Later location surveys showed that these clusters continued to move until about Day 114, approximately 60 days after all the pile driving in that area had been completed.

FIG. 10.—LATERAL MOVEMENTS OF PILES IN CLUSTER A-7, CASE A1

FIG. 11.—LATERAL MOVEMENTS OF PILE CLUSTERS, CASE A1

All Distances In Feet

ANALYSIS OF CASE

Effect on Soil Characteristics.—The effects of pile driving on the strength of the clay at this site and the progress of subsequent consolidation within the pile clusters have been discussed elsewhere (15, 21, 22). At many of the clusters, it is evident that the soft clay had an opportunity to consolidate appreciably during the interval between pile driving and reseating operations.
Effects of Pile Type.—The magnitudes of ground and pile heave were large because the piles were of a type associated with high displacements. The heave was especially serious because of the slip joint between pile sections. The slip joint allowed concrete piles to elongate at the point because the tensile strength of the concrete was not sufficient to resist the upward pull of the soil on the shell sections. If the 28-day strength of the concrete had been equal to 3,000 psi, the tensile capacity of the cured plain concrete at the slip joint would have been about 14 tons. The maximum pull of the soft clay (completely remolded) along the shell sections may be estimated as about 13 tons. Since at least one day elapsed between driving and concreting the piles, the strength of the clay was greater than the remolded strength and the upward pull on the pile shells was undoubtedly greater than 14 tons. The lower pipe sections of the piles remained stationary since they probably developed a frictional resistance of at least 15 tons in the hard clays and compact silts.

Effects of Foundation Geometry.—Grouping of piles in clusters caused a buildup of stress in the soil at the location of the clusters. Thus, after being driven, the piles within a cluster had a tendency to move laterally outward from the center of the cluster for several weeks as stress relaxation took place within the soil. If the piles had been driven at a uniform spacing throughout the foundation area, the stresses produced by pile driving would have been rather uniform throughout the area and there would have been no reason to expect further soil movement.

The existence of three levels of excavation in the foundation also had an effect upon the movement of the driven piles. In many instances, soil was displaced during driving toward the open area of a nearby excavation, and previously driven piles were displaced in the same direction. For instance, the location surveys conducted after Day 80 showed that many piles near the construction slopes were displaced toward the lower excavation levels during driving. The different excavation levels also led to delayed movements of the soil and the piles.

The general sequence of construction operations had an important influence on soil and pile movement. Initially, three pile drivers were positioned in the western extremities of the excavation and driving proceeded eastward toward the central area of the foundation. Driven piles were displaced to the west, away from the central area, by the subsequent driving. The combined effects on pile movements of foundation geometry and pile driving sequence may be deduced from the behavior of the pile clusters along row 15, mentioned previously. The piles along row 15, driven after all the piles to the west of that row were in place, moved eastward toward the lower excavation levels as they were driven. Then when the piles at the lower level along rows 13 and 12 were driven, between Day 41 and Day 57, the piles along row 15 were displaced to the west away from the slopes. The initial eastward and later westward movements produced little net displacement of the row-15 clusters. The location surveys showed only small displacement as of about Day 59. After all the piles in the central area were driven, no further changes in the soil stresses were created. After about Day 60 there existed larger lateral forces in the soil to the west of row 15 than in the soil to the east of that row because the piles to the west penetrated a greater depth of soil than did the piles to the east. The unbalanced applied forces in the soil produced creep movements toward the lower foundation level. The soil carried the piles toward the east in agreement with the measured displacements for clusters J-15, H-15, and I-15.
Summary Case. — (1) Pile heaves of 5 in. or more were produced by driving closely-spaced displacement piles into a deposit of soft clay overlaid by hard clay and compact silt; (2) the soft clay acted as an incompressible material in the immediate vicinity of any one pile cluster during the few days required for driving the piles in that cluster; (3) the piles in a cluster heaved during driving within that cluster and during driving of adjacent clusters; (4) the piles moved laterally away from areas of subsequent driving during and for some time after driving; and (5) different excavation levels within the foundation also influenced the amount and direction of the lateral movement.

A comprehensive analysis of pile heave problems at another site is contained in Fig. 6 (corresponding in this study to case B1).

ESTIMATE OF PILE HEAVE

Pile heave data from nine other case histories support the observations made in the preceding summary. However, in only two other cases, A2, and

### TABLE 3.—ESTIMATED ADHESION VALUES

<table>
<thead>
<tr>
<th>Clay</th>
<th>Soil</th>
<th>Average cohesion, in pounds per square foot</th>
<th>Tomlinson correction factor (4)</th>
<th>Estimated adhesion, in pounds per square foot</th>
<th>Relative adhesion per foot of pile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiff clay</td>
<td>C1</td>
<td>1,800</td>
<td>0.75</td>
<td>1,350</td>
<td>1.35 A</td>
</tr>
<tr>
<td>Very stiff clay</td>
<td>C2</td>
<td>3,000</td>
<td>0.50</td>
<td>1,500</td>
<td>1.50 A</td>
</tr>
<tr>
<td>Stiff clay</td>
<td>C3</td>
<td>2,900</td>
<td>0.70</td>
<td>1,200</td>
<td>1.20 A</td>
</tr>
<tr>
<td>Hard clay</td>
<td>C4</td>
<td>4,000</td>
<td>0.40</td>
<td>1,600</td>
<td>1.60 A</td>
</tr>
</tbody>
</table>

### TABLE 4.—PILE HEAVES, CASES A1, A2, B7

<table>
<thead>
<tr>
<th>Case</th>
<th>Estimated maximum pile heave, in inches</th>
<th>Observed maximum pile heave, in inches</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>5-1/12</td>
<td>5 to 5-1/2</td>
</tr>
<tr>
<td>A2</td>
<td>24</td>
<td>21 to 24</td>
</tr>
<tr>
<td>B7</td>
<td>1-7/8</td>
<td>1-3/4</td>
</tr>
</tbody>
</table>

B7, are comprehensive data available. Fig. 12 shows, for case A2, the plan and elevation of a bridge foundation. The pile heave in the center of the excavation for each pier was approximately 24 in., and the soil surface heave was approximately 50 in. Case B7 has been described extensively elsewhere (1,2).

In a uniformly heaving mass of clay the upward movement would vary linearly with distance above the base of the clay. Inextensible vertical piles embedded in the clay would be lifted by the relative rise of the soil with respect to the upper part of the pile, but the rise of the lower part of the pile would exceed that of the surrounding soil at that level. Therefore, the half of the pile would be acted on by downward forces tending to reduce the total uplift of the pile. If the consistency of the soil varies with depth, a surface a-a, Fig. 13, may be found at which the relative movement between soil and pile is zero. As an approximation, the pile heave may be considered roughly equal to the heave of the soil on the assumption that no heave takes place below a-a. The depth, d, is estimated by balancing the potential upward and downward adhesive forces on the upper and lower parts of the pile, respectively.

The procedure is illustrated for case A2. The soil-pile adhesion is estimated on the basis of the relationship between soil cohesion and soil-pile adhesion proposed by Tomlinson (25). The estimated adhesion values are given in Table 3.

For these assumed relative adhesion values, the upward pull on the upper part of the 140-ft piles would equal the resistance to movement of the remaining lower part for a depth of about 73 ft to the surface of zero relative displacement, illustrated as follows:

<table>
<thead>
<tr>
<th>Upward Pull</th>
<th>Resistance to Movement</th>
</tr>
</thead>
<tbody>
<tr>
<td>65 ft of soil C1</td>
<td>22 ft of soil C2</td>
</tr>
<tr>
<td>65 \times 1.35 A = 88 A</td>
<td>22 \times 1.50 A = 33 A</td>
</tr>
<tr>
<td>8 ft of soil C2</td>
<td>30 ft of soil C3</td>
</tr>
<tr>
<td>8 \times 1.50 A = 12 A</td>
<td>30 \times 1.40 A = 42 A</td>
</tr>
<tr>
<td>15 ft of soil C4</td>
<td>Total 99 A</td>
</tr>
<tr>
<td>15 \times 1.60 A = 24 A</td>
<td></td>
</tr>
</tbody>
</table>

The pile heave is then estimated as about (140 - 73)/140 times the total soil heave, or about 24 in. The estimated maximum pile heave is approximately equal to the observed pile heaves near the center of the foundation. For cases A1 and B7 the maximum pile heave may be estimated in the same way. Table 4 shows the results of such estimates and furnishes a comparison with observed pile heaves.

The close agreement of the values shown in Table 4 is fortuitous, but it would appear that the procedure is reasonable. It should be applied only if the piles are to be driven in a rather regular manner from one side of a foundation to the opposite side. A driving sequence which tends to confine the soil or restrict its movement to a certain direction may cause greater soil heave in certain areas of a foundation than would be predicted on the basis of the procedure, as demonstrated by case B2. The procedure should not be used if the soil may decrease in volume significantly during driving. For example, in case B6 (5,32,33) the densification of granular layers during pile driving probably reduced soil heave, and the densifying strata also acted to hold down driven piles. The average pile heave was approximately equal to 1/10 of the observed soil heave at this site.

In several other cases the action of a very stiff or strong stratum near the pile tip in holding down the piles against upward pull of heaving upper soils was apparent. Obviously, the efficacy of such holding soils depends upon the characteristics of the piles themselves. In case A3, inextensible pipe piles...
CONCLUSIONS

1. Significant soil displacement occurs during pile driving in fine grained soil deposits. Saturated insensitive clay soils behave incompressibly during pile driving.

2. At four sites where piles were driven into such clay soils, approximately half the volume of displaced soil appeared as surface heave within the area of the pile foundation while the remaining half appeared as surface heave outside the foundation area.

3. Given the conditions of a saturated, insensitive clay subsoil, a regular pile driving sequence, and a level foundation ground surface, the normalized soil surface heave within the foundation area may be estimated as half the volumetric displacement ratio for the site.

4. When piles are driven into sensitive clays, the resultant soil displacement, especially beyond the limits of the area enclosed by the piles themselves, may be less than that produced during driving in insensitive clays. Remolded soil may be extruded around the pile at the ground surface.

5. When piles penetrate alternating strata of fine-grained soil and granular materials, the observed surface heave may be much less than that which would have occurred in insensitive clay soils.

6. When large differences in elevation exist within the foundation area, pile driving may displace the soil laterally preferentially towards the areas in which the lower elevations occur. The movements may continue for some time after driving has ceased.

7. If the sequence of pile driving involves driving piles first along the perimeter of the foundation, the heave of the soil surface in the central area of the foundation is increased and that of the surrounding area correspondingly decreased.

8. The magnitude of the pile heave in a foundation, which differs from the heave of the ground surface, may be estimated by a simple procedure. Pile heaves estimated by this procedure agree quite well with the values observed.

9. Lateral movements of soil and piles may occur during pile driving and for a considerable length of time thereafter. In general, driven piles tend to be displaced away from subsequent driving.

APPENDIX.—REFERENCES


INTRODUCTION

Although much experimental and theoretical effort has recently gone into investigation of the failure loads of footings placed initially on the surface of uniformly dense sand, there are still some features which require further attention. In the first place, most current theories use contact stress and friction assumptions which produce sharply discontinuous vertical stress distributions at the center of the footing base. Secondly, the failure loads of model footings are strongly influenced by the settlements which are required to mobilize the full shear strength in the failure zones. This is usually treated empirically by superposition of solutions obtained separately for zero surcharge and for zero self-weight. Finally, although it is usually possible to obtain fair agreement between theoretical and laboratory results by using triaxial tests to describe the average shear strength of the sand, it is generally accepted that model tests overestimate the bearing capacity of full scale footings by an undetermined amount. Density changes observed beneath model foundations (15) show that the soil strength varies considerably in failure zones, and the usual assumption of constant angle of shearing resistance is therefore a major simplification of sand behavior.

Solutions to the smooth footing problem using the numerical techniques of plasticity analysis have been presented by, e.g., Sokolovskii (20) and Larkin (14). In practice, however, footings are not perfectly smooth and the influence on bearing capacity of shear stresses mobilized across the base of the footing has been outlined by Gorbunov-Possadov (9), Hansen and Christensen (11), and Karafiath (13). The purpose of this paper is to examine the effects of various...